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Trends Research Characterization of TiO_2 Thin Films as Solar Cell Materials (2015-2024): A Systematic Review

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Abstract: Research in the field of solar cells continues to increase along with the development of the times and human needs for renewable energy sources. One of the fields of study that is often used as a research topic is the development of Thin Film Solar Cells or known as Thin Film Solar Cells (TFSC). This research aims to identify and analyze research trends of synthesis of $Ti0_2$ thin films as solar cell materials. This research method is descriptive and analytical. The data used in this research was obtained from documents indexed by Google Scholar from 2015-2024 using Publish or Perish and Dimension.ai. Research procedures use PRISMA guidelines. The data identified and analyzed are the type of publication, publication source, and the title of research on synthesis of $Ti0_2$ thin films as solar cell materials that is widely cited. The data analysis method uses bibliometric analysis assisted by VOS viewer software. The results of the analysis show that research trend on synthesis of TiO_2 thin films as solar cell materials indexed by Google Scholar from 2015 to 2024 has experienced increases and decreases. There are many documents in the form of articles, proceedings, chapters, preprints, monograph and edited books that discuss research about synthesis of Ti02 thin films as solar cell materials. Key words that are often used in research about it are dye sensitized cell, electrode, electron, characterization, etc.

Keywords: Characterization; Review; Solar cell; TiO_2 thin films

Introduction

Research in the field of solar cells continues to increase along with the development of the times and human needs for renewable energy sources (Mitrašinović, 2021; Rathore et al., 2021). Research about solar cells began with the first generation that utilized silicon and germanium as the main raw materials, then the second generation utilizing semiconductor raw materials, and the third generation utilizing organic materials in the form of Dye-Sensitised Solar Cells (DSSC) (Efaz et al., 2021; Roy et al., 2021). DSSC are a type of third-generation solar cells that utilize the principle of photoelectrochemistry. This type of solar cell is believed to be able to provide an alternative energy concept with more affordable production costs and simpler fabrication technology compared to its predecessor solar cells made of crystalline silicon. DSSC components consist of several parts, namely dye as a photo; sensitizer, electrolyte to supply electrons to the dye, catalyst (counter electrode) to attract electrons into the electrolyte, and a semiconductor layer that uses TiO_2 as dye adsorption and electron transport.

The main performance of this cell depends on the dye used as a photosensitizer. The absorption spectrum of the dye and the anchorage of the dye to the TiO_2 surface are important parameters in determining the efficiency of the cell. Dye plays an important role in the development of high performance DSSC. Dye needs to have requirements such as strong absorption in absorbing the visible light spectrum, carrying the appropriate bond of chemical groups to be bound to the

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semiconductor and can inject electrons into the semiconductor surface. Continuously increasing research studies in the field of solar cell technology are certainly because the main source of this technology is utilizing sunlight which is unlimited to replace other energy in the future. Solar cells are a technology that is composed of semiconductor materials with the principle of converting sunlight into electrical energy through the photovoltaic effect (Brédas et al., 2017; Husain et al., 2018; Nayak et al., 2019). One of the fields of study that is often used as a research topic is the development of Thin Film Solar Cells or known as Thin Film Solar Cells (TFSC) (Saif et al., 2023; I. Sharma et al., 2022; Underwood et al., 2023).

Thin Film Solar Cells (TFSC) are one type of solar cell whose development process is by adding thin layer technology as the basic material for making solar cells (Doyan et al., 2022; Rizaldi & Ziadatul Fatimah, 2023). This thin layer becomes one of the components that will later be absorbent to sunlight. The development of thin films based on solar cells can be synthesized or made using various compounds, both organic, inorganic, metal, and metal-organic, which can be conductors, semiconductors, superconductors, and even insulators (Liu et al., 2022; Meng et al., 2020; Song, 2021). One of the compounds that is often used in research on thin films based on solar cells is Titanium Dioxide (TiO_2) (Eliyana et al., 2020; Suriani et al., 2019). Titanium Dioxide (TiO_2) is a type of semiconductor material that has environmentally friendly properties because it does not produce pollutants, requires relatively low costs, has a small energy band gap of around 3.2 eV, has good stability, and is free from photo corrosion (Setyawan et al., 2024; Shabrina et al., 2023). The TiO_2 compound has three types of crystal structures, namely anatase, brookite, and rutile (Allen et al., 2018; Eddy et al., 2023; Žerjav et al., 2022).

TiO_2 (titanium dioxide) is a commonly used material in DSSC dye-sensitized solar cells. TiO_2 material has a porous structure and high surface roughness providing a large surface area for light absorption. Light entering through TiO_2 is absorbed by the dye bound to the TiO_2 surface, and this light energy is converted into electrons. The electrons injected into TiO_2 can then be used to generate electric current through an external circuit that allows it to last for a long time (Boro et al., 2018). However, if reviewed more deeply in terms of physical characteristics, the surface of the thin layer is still rough because the TiO_2 compound is basically in powder form (Bhernama et al., 2017). Therefore, this research wants to know the research trend of the synthesis of TiO_2 thin films as solar cell materials. It is hoped that this research can become a reference in developing further research related to TiO_2 thin films as solar cell materials.

Method

This research method is descriptive and analytical, which aims to understand and describe research trends in the characterization of TiO_2 thin films as solar cell materials. The data used in this study was obtained from information sources indexed by Google Scholar using analytical tools such as Publish or Perish and Dimension.ai. To carry out a search on Google Scholar, keywords related to research trends on the characterization of $Ti0_2$ thin films as solar cell materials.

In this research, an analysis was carried out on 1,000 documents that had been indexed by Google Scholar between 2015 and 2024. The Google Scholar database was chosen as a place to search for documents because Google Scholar applies consistent standards in selecting documents to be included in its index, and Google Scholar displays more documents than the top databases (Hallinger & Chatpinyakoop, 2019; Hallinger & Nguyen, 2020; Zawacki-Richter et al., 2019). To filter data that has been collected via Publish or Perish, researchers used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines.

Result and Discussion

This research aims to describe research trends on characterization of TiO_2 thin films as solar cell materials conducted from 2015 to 2024. Research documents on research trends characterization of TiO_2 thin films as solar cell materials are taken from documents from 2015 to 2024. Figure 1 shows that the trend in research on the characterization of $Ti0_2$ thin films as solar cell materials from 2015 to 2024 experienced an increase and decrease in the number of publications. Where the research trend is increase in the number of publications from 2015 to 2016. However, in 2017 to 2018 the research trend on the characterization of TiO_2 thin films as solar cell materials has decreased.

After that, the research trend increases again until 2021, before decrease again in 2022 to 2024. The variative trend in research on the characterization of $Ti0_2$ thin films as solar cell materials indicates that research in the field of solar cells continues to increase along with the development of the times and human needs for renewable energy sources. In 2015 there were 23 publications related to the characterization of TiO_2 thin films as solar cell materials, then this will continue to increase to 24 publications in 2016. After that it decreased to 11 publications in 2018 before increased again in 2021 with 27 publications. Below are also table 1 presented research of characterization of TiO_2 thin films as solar cell materials based on the type of publication.

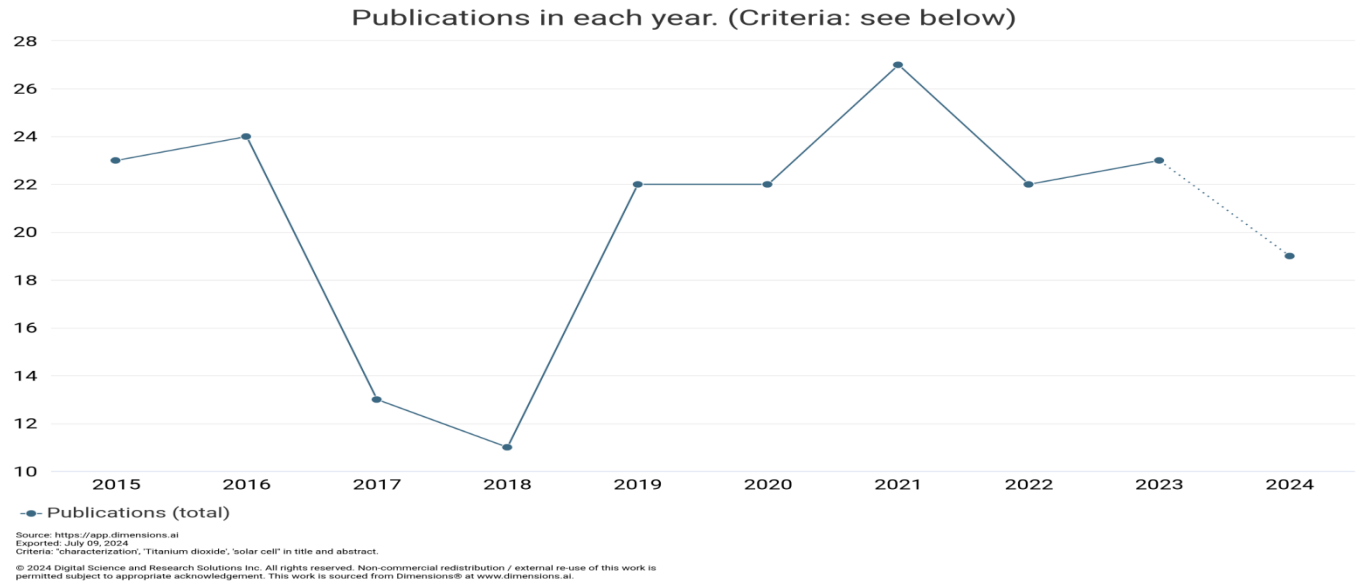

Figure 1. Research trends in characterization of TiO_2 thin films as solar cell materials

Table 1. Trends in Characterization of TiO_2 Thin Films as Solar Cell Materials Research Based on Publication Types

Publication Type	Publications
Article	253
Proceeding	20
Chapter	15
Preprint	5

Based on Table 1, it is known that research characterization of $Ti0_2$ thin films as solar cell materials from 2015 to 2024 contained in 4 types of publications. In the form of articles there were 253 documents, proceedings as many as 20 documents, chapter with 15 documents and preprints as many as 5 documents. Research characterization of TiO_2 thin films as solar cell materials in article form is the type of publication that contains the most research compared to other types of publications. Meanwhile, the type of publication contains the least amount of research results characterization of TiO_2 thin films as solar cell materials is a preprint (Mîndroiu et al., 2023; He et al., 2023). Research conducted by (2019), Eddy et al. (2023) states that an article is a complete factual essay of a certain length created for publication in online or print media (via newspapers, magazines or bulletins) and aims to convey ideas and facts that can convince and educate. These articles are usually published in scientific journals both in print and online (Suseno & Fauziah, 2020).

Table 2. Top 10 Sources Title Trend of Characterization of TiO_2 Thin Films as Solar Cell Materials Research in 2015-2024

Name	Publications	Citations	Citations Mean
IOP Conference Series Materials Science and Engineering	8	31	3.88
AIP Conference Proceedings	6	9	1.50
Journal of Physics Conference Series	6	10	1.67
The Journal of Physical Chemistry C	5	206	41.20
Materials Today Proceedings	5	35	7.00
Optik	4	55	13.75
Journal of Materials Science: Materials in Electronics	4	5	1.25
IEEE Transactions on Electron Devices	3	8	2.67
Nanotechnology	3	91	30.33
Synthetic Metals	3	36	12.00

Table 2 presents the top ten (10) source title trends in research on the characterization of TiO_2 thin films as solar cell materials that are frequently cited by other researchers in this regard. Table 2 shows that the most widely published source of research trends on characterization of TiO_2 thin films as solar cell materials is the IOP Conference Series Materials Science and Engineering, namely 8 publications with 31 citations and an average citation of 3.88. IOP Conference Series: Materials Science and Engineering (MSE) is an Open Access proceedings journal provides a fast, versatile and cost-effective proceedings publication service. IOP

Conference Series: Materials Science and Engineering provides a comprehensive solution for materials science and engineering conferences. Below are also table 3 presented top ten (10) article title trends in research on characterization of TiO_2 thin films as solar cell materials which are often cited by other researchers related to this matter.

Table 3 shows that research on the characterization of TiO_2 thin films as solar cell materials that is widely cited by other researchers is about "Titanium dioxide hole-blocking selective contact to enable double-heterojunction crystalline silicon-based solar cell" which is 16.78 (Nagamatsu et al., 2015). Then the research entitled "Enhanced photovoltaic performance of dye-sanitized solar cell with tin doped titanium dioxide as photoanode materials" was cited 9.33 times/year. Research by Govindaraj et al. (2015) entitled "Sol–gel synthesized mesoporous anatase titanium dioxide nanoparticles for dye sensitized solar cell (DSSC) applications" is also widely cited by other researchers, namely 5.44 per year. Perarasan et al. (2021) in their research entitled "Copper doped titanium dioxide for enhancing the photovoltaic behavior in solar cell" was cited 5.00 per year.

This research data is comparable to data on the increasing trend of research on the characterization of $Ti0_2$ thin films as solar cell materials from 2015 to 2024. This means that in that year, research related to it was continuously cited by other researchers. In the articles researched and written by these researchers, there are many terms related to characterization of $Ti0_2$ thin films as solar cell materials. Below are presented ten (10) popular keywords related to characterization of TiO_2 thin films as solar cell materials.

Table 3. Top 10 Citations on Trend of Characterization of TiO_2 Thin Films as Solar Cell Materials in 2015-2024

Cites/year	Year	Author	Title
16.78	2015	K A Nagamatsu et al.	Titanium dioxide/silicon hole-blocking selective contact to enable double-heterojunction crystalline silicon-based solar cell
9.33	2021	Mahmoud, Z. H.; Al-Bayati, R. A.; Khadom, A. A.	Enhanced photovoltaic performance of dye-sanitized solar cell with tin doped titanium dioxide as photoanode materials
5.44	2015	R govindaraj, M S pandian, P ramasamy & S mukhopadhyay	Sol–gel synthesized mesoporous anatase titanium dioxide nanoparticles for dye sensitized solar cell (DSSC) applications
5.00	2021	T Perarasan, J P Isaqu, M K Arivalagan, N Rajamanickam	Copper doped titanium dioxide for enhancing the photovoltaic behavior in solar cell
4.89	2015	A Arunachalam, s. Dhanapandian, C Manoharan, R Sridhar	Characterization of sprayed TiO2 on ITO substrates for solar cell applications
4.67	2021	V. Gayathri, M. Rameshbabu, S. Sasiflorence, K Ravichandran	Influence of La on nano titanium dioxide (TiO2) based solar cell
3.44	2015	Mohammed, Ari A, Ahmad, Alan S. Said, Azeez, Wafaa A.	Fabrication of Dye Sensitized Solar Cell Based on Titanium Dioxide (TiO2)
2.57	2017	A.M. Ramli, M.Z. Razali, Norasikin A. Ludin	Performance enhancement of dye sensitized solar cell using graphene oxide doped titanium dioxide photoelectrode
2.50	2018	R Govindaraj, N Santhosh, M S Pandian, P Ramasamy & M Sumita	Fabrication of stable dye-sensitized solar cell with hydrothermally synthesized titanium dioxide nanorods as a photoanode material
0.25	2016	I N Setiawan, I A D Giriantari, W G Ariastina, I B A Swamardika	Characterization of titanium dioxide (TiO2) thin films as materials for dye sensitized solar cell (DSSC)

Table 4 shows that the on of keywords that often appear related to research on the the characterization of $Ti0_2$ thin films as solar cell materials are dye sensitized solar cells efficiency, 9 times with a level of 0.85. Research about solar cells began with the first generation that utilized silicon and germanium as the main raw materials, then the seconds generation utilizing semiconductor raw materials, and the third generation utilizing organic materials in the form of Dye-Sensitised Solar Cells (DSSC). Table 4 also shows that photovoltaic performance is also a keyword that appears frequently in research trends on the characterization of $Ti0_2$ thin films as solar cell materials, namely 10 times with a relevance of 1.53. There are many articles that investigate about photovoltaic performance of DSSC (Chen et al., 2018; Lim et al., 2015; K. Sharma et al., 2018).

Table 4. Keywords on Trend characterization of TiO_2 Thin Films as Solar Cell Materials Research in 2015-2024

Terms	Occurrences	Relevance
Electron transport layer	15	8.42
Perovskite solar cell	36	4.50
X ray diffraction	10	2.69
Photovoltaic performance	10	1.53
Photovoltaic characteristic	11	1.35
Nanostructure	15	0.98
Photoelectrode	15	0.88
Dye sensitized solar cells	9	0.85
Synthesis	66	0.67
Fabrication	46	0.60

Below are the visualization is accomplished by generating a landscape map, which offers a visual representation of subjects related to scientific studies. The outcomes of bibliometric mapping for the co-word network in articles related to the topic characterization of TiO_2 thin films as solar cell materials are illustrated in Figure 2. Figure 2 shows the results of bibliometric keyword mapping on research trends on the characterization of TiO_2 thin films as solar cell materials. In Figure 2 there are 51 keyword items that are often used in research on the characterization of $Ti0_2$ thin films as solar cell materials from 2015 to 2024. Figure 2 also contains 4 clusters, where the first cluster is colored red and consists of 14 keyword items, namely dye sensitized solar cell, electron transport layer, perovskite solar cell, photovoltaic characteristic, etc. The second cluster in green consists of 14 keyword items, namely nanoparticle, nanostructure, x ray diffraction, etc. The third cluster in blue consists of 13 keyword items, namely efficiency, electrode, photoelectrode, etc. The fourth yellow cluster consists of 10 keyword items, namely fabrication, graphene oxide, photoanode, synthesis, etc.

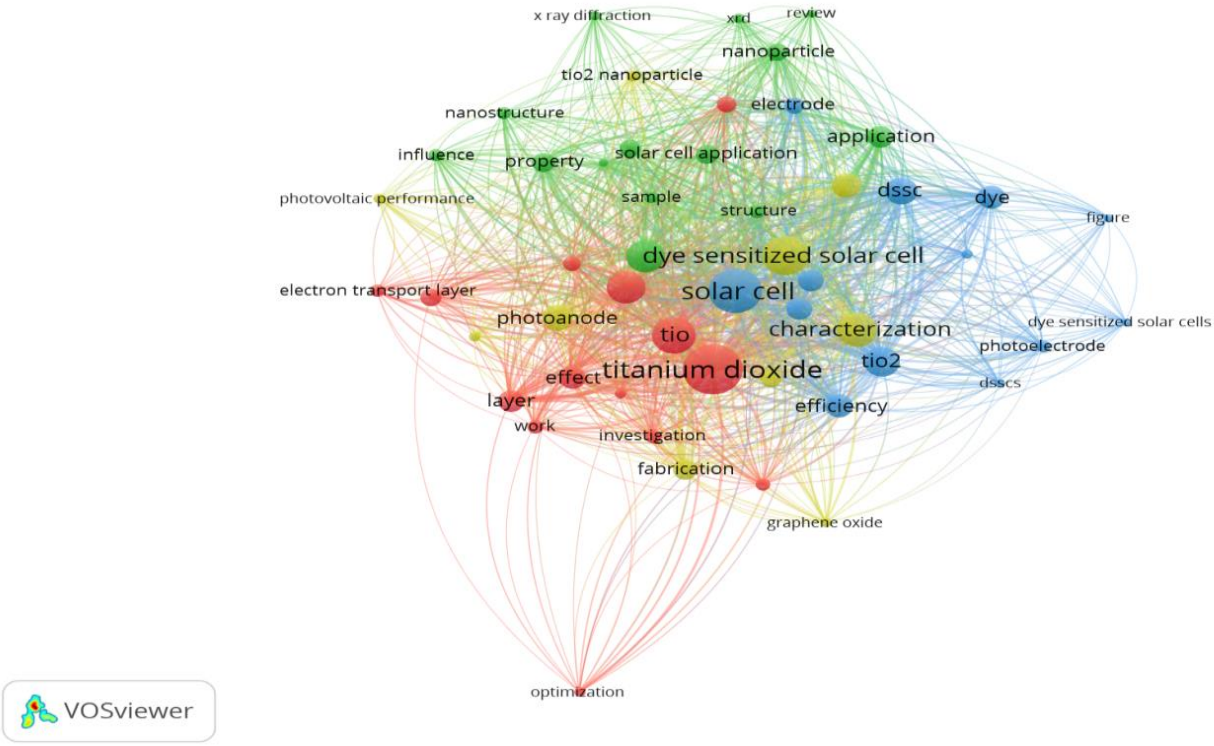

Figure 2. Network visualization on trend characterization of TiO_2 thin films as solar cell materials research

Figure 2 above also shows that network visualization shows the network between the terms being visualized. Keywords classified into four clusters are arranged in a color chart showing the divisions that are connected to each other. The results of this analysis can be used to determine keyword research trends in the last year. This analysis shows several keywords that are often used in research on the characterization of TiO_2 thin films as solar cell materials. The more keywords that appear, the wider the visualization displayed. Below are also presented keywords regarding the characterization of TiO_2 thin films as solar cell materials based on overlay visualization. Figure 3 shows the trend of keywords related to research on characterization of TiO_2 thin films as solar cell materials in Google Scholar indexed journals from 2015 to 2024.

Trends in the themes of writing articles related to characterization of TiO_2 thin films as solar cell materials from the oldest to the newest year are marked with purple, blue themes, turquoise, dark green, light green and yellow. In the picture below you can see that the dye sensitized solar cell, photoelectrode, photovoltaic, etc. This shows that these keywords were widely used by researchers in 2018. In 2019, the keywords that frequently appeared were perovskite solar cell, graphene oxide, x ray diffraction, etc.

Research on characterization of TiO_2 thin films as solar cell materials is one area of research that has developed rapidly in recent years. The following also presents keywords for characterization of $Ti0_2$ thin films as solar cell materials research based on density visualization.

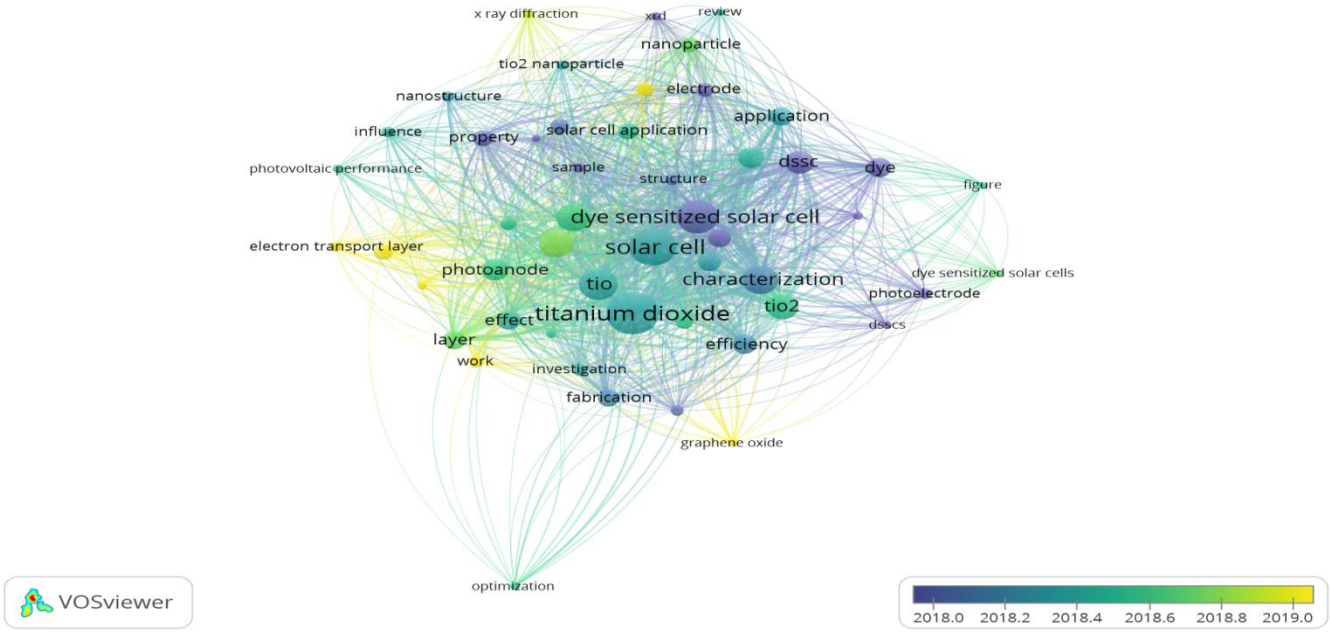

Figure 3. Overlay visualization on trend characterization of $Ti0_2$ thin films as solar cell materials research

Figure 4 shows density visualization. The density of research themes is shown in bright yellow. The brighter the colors of a theme, the more research is done. The fainter the color means the theme is rarely researched (Kaur et al., 2022; Liao et al., 2018). Faintly colored themes such as electron transport layer, nanocrystalline, graphene oxide are dimly colored keywords. This shows that these keywords can be used as a reference for further research. Eddy et al. (2023) and Doyan et al. (2023b) stated that yellow indicates keywords that are currently and frequently used in research, like dye sensitized solar cell, TiO_2, synthesis, photoanode, etc.

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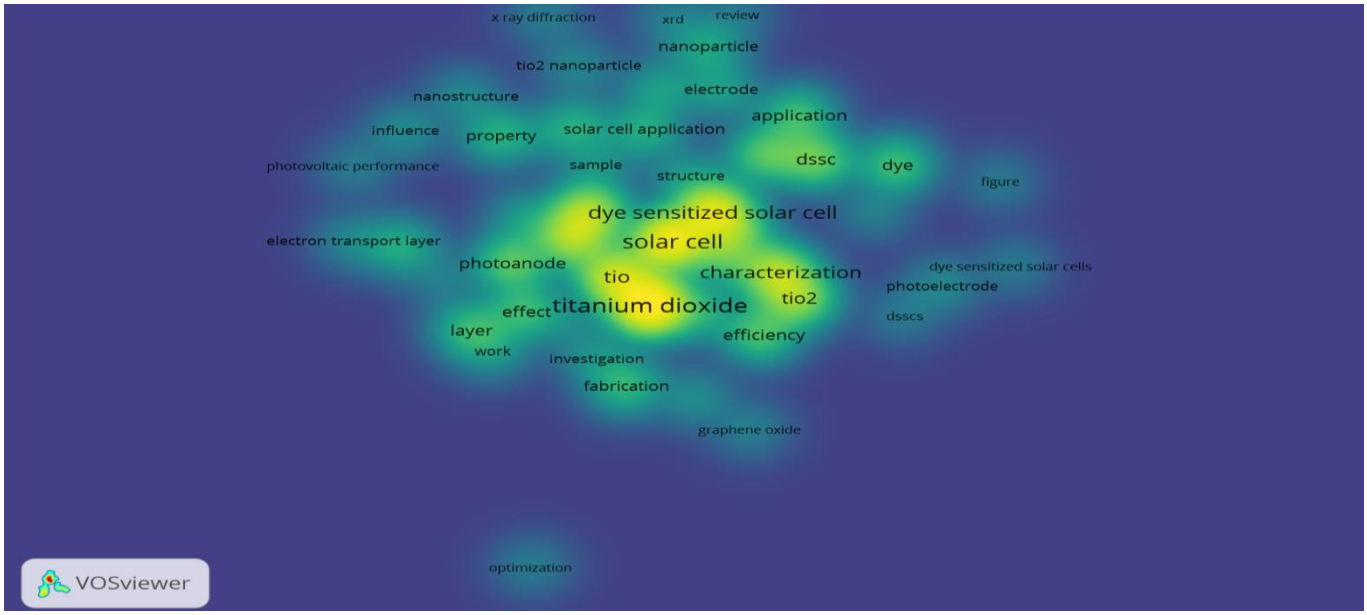

Figure 4. Density visualization on trend characterization of TiO_2 thin films as solar cell materials research

Overall, continuously increasing research studies in the field of solar cell technology are certainly because the main source of this technology is utilizing sunlight which is unlimited to replace other energy in the future. The research trend in characterization of $Ti0_2$ thin films as solar cell materials is expected to continue to develop in the next few years (Djordjević et al., 2023; Nowsherwan et al., 2023; Mohallem et al., 2018). This can be done by one of the fields of study that is often used as a research topic is the development of Thin Film Solar Cells or known as Thin Film Solar Cells (TFSC). However, if reviewed more deeply in terms of physical

characteristics, the surface of the thin layer is still rough because basically the TiO_2 compound is in powder form, so treatment is still needed to maximize the potential of this thin layer so that it can absorb sunlight not only in ultraviolet light but also in visible light (Verma et al., 2024; Yang & Cheng, 2020; Ngoc et al., 2019; Hassaan et al., 2023). The treatment that can be done to improve this performance is by carrying out a dye sensitization process and adding doping.

Conclusion

Research on trends in the characterization of $Ti0_2$ thin films as solar cell materials has urgency high. Research studies in the field of solar cell technology are certainly because the main source of this technology is utilizing sunlight which is unlimited to replace other energy in the future. The research trend on the characterization of TiO_2 thin films as solar cell materials indexed by Google Scholar from 2015 to 2024 has experienced increases and decreases. There are many documents in the form of articles, proceedings, chapters, and preprints that discuss research into the characterization of $Ti0_2$ thin films as solar cell materials. Key words that are often used in research about it are dye sensitized cell, synthesis, fabrication, photovoltaic, etc.

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Author Contributions
Conceptualization, A. D.; methodology, S.; validation.; formal analysis, M. T.; investigation, S. A.; resources, A. D.; data curation, M. T.; writing—original draft preparation, S. A.; writing—review and editing, A. D.: visualization, M. T., and S. All authors have read and agreed to the published version of the manuscript.

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